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Local Interaction Simulation Approach for Massively Parallel Computation of Ultrasonic Guided Waves

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Abstract: This paper presents the Local Interaction Simulation Approach (LISA) for the efficient modeling of ultrasonic guided waves. Firstly, LISA theory is introduced based on the Finite Difference (FD) formulation and the Sharp Interface Model (SIM). The anisotropic material properties and viscoelasticity are considered in the elastodynamic equations, which enables the modeling of composite laminates with arbitrary stacking orientations. A penalty method is integrated within the formulation to capture the contact acoustic nonlinearity during wave crack interactions. The LISA model is highly efficient due to the finite difference formulation and the parallel implementation using the Compute Unified Device Architecture (CUDA) technology. The computation is executed in a massively parallel manner on powerful Graphical Processing Units (GPUs), which allows the efficient simulation of ultrasonic guided waves in large inspection domains for Structural Health Monitoring (SHM) and Nondestructive Evaluation (NDE) procedures. Three case studies are presented: (1) wave propagation in anisotropic composite panels with experimental validations using the Doppler Scanning Laser Vibrometry; (2) nonlinear interactions between guided waves and fatigue cracks verified with commercial finite element package; (3) guided wave propagation and damage detection in a rail track compared with experimental measurements. This paper finishes with summary, concluding remarks, and suggestions for future work.

Keywords: Local interaction simulation approach, numerical modeling, parallel computing, guided waves, structural health monitoring, nondestructive evaluation

1. Introduction

Ultrasonic guided waves have been extensively studied as a powerful tool for damage detection [Su and Ye (2009)]. Understanding the wave mechanics is of critical importance for Structural Health Monitoring (SHM) and Nondestructive Evaluation (NDE). However, the efficient modeling of guided waves is a challenging task. The challenges mainly arise from the following aspects: (1) the multi-modal and dispersive nature of guided waves; (2) the complex wave structure and wave damage interactions. Simulating the wave dynamics for high-frequency, short-wavelength ultrasonic guided waves over a large propagation distance is usually computationally prohibitive due to the

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dense discretization both in temporal and spatial domain.

Enormous research efforts have been exerted on developing accurate, efficient, versatile modeling schemes to satisfy the desperate need for SHM and NDE modeling tasks. Among such endeavors, the local interaction simulation approach (LISA) has been developed, acquiring more and more modeling capabilities to handle complex simulation tasks. Delsanto et al. first derived the 1-D, 2-D, and 3-D LISA formulations for isotropic, heterogeneous materials executed on Connection Machines [Delsanto et al. (1997)]. LISA underwent considerable progress during the past decade, with its application in metallic structures [Lee and Staszewski (2003)], extension to general anisotropic materials [Nadella and Cesnik (2013)], coupled field capabilities [Nadella and Cesnik 2014], hybridization with other numerical methods [Shen and Cesnik (2016)], and execution on powerful Graphics Processing Units (GPU) with Compute Unified Device Architecture (CUDA) technology [Packo et al. (2015)]. In the authors' recent study, a penalty method was deployed to introduce contact dynamics into the LISA formulation to simulate contact acoustic nonlinearity (CAN) [Shen and Cesnik (2017)]. The GPU implementation has substantially facilitated low-cost supercomputing for ultrasonic elastic waves in large-scale structures.

This paper presents LISA modeling technique for highly efficient computation of ultrasonic guided waves for SHM and NDE applications. The LISA fundamentals and its GPU implementation will be introduced. Three numerical case study examples will follow to demonstrate LISA's prowess in handling various aspects of the modeling challenges. First, guided wave propagation in anisotropic composite panels will be modeled and compared with experiential measurements, which aims to present LISA's capability in considering material anisotropy and the guided wave attenuation due to damping. Second, guided wave interaction with a fatigue cracks will be modeled and verified against commercial finite element package, which would demonstrate LISA's ability to simulate nonlinear interactions between interrogating waves and the damage. Finally, guided wave propagation in a rail track with a fatigue crack will be presented and validated with experimental measurements, which illustrates LISA's versatility in handling wave propagation in geometrically complex waveguides.

2. LISA Framework for Modeling Elastic Waves in Solids

This section introduces the fundamentals of the LISA framework, including the solving procedure for the elastodynamic wave equations and the parallel implementation using CUDA technology executed on powerful graphic cards.

2.1. LISA Framework

Figure 1 presents the LISA framework, showing its derivation procedure as well as the new features. LISA approximates the partial differential elastodynamic wave equations with finite difference quotient expressions. The coefficients in LISA iterative equations (IEs) depend only on the local physical material properties. A sharp interface model (SIM) was used to enforce the stress and displacement continuity between the neighboring cells and nodes. Therefore, changes of material properties in the cells surrounding a computational node can be captured through these coefficients. The details of formulation derivation can be found in [Nadella and Cesnik (2013)]. Guided wave generation can be achieved with an efficient frequency domain local FEM. Details of this hybrid approach can be found in [Shen and Cesnik (2016)]. Damping effects are considered based on the 3-D Kelvin-Voigt viscoelasticity model. A viscosity matrix is introduced for a generic lamina with arbitrary stacking angle to capture the directional and coupling damping effects. It should be noted that the IEs with damping effects require the results from previous three time steps to determine the displacement result at current time step. A commercial preprocessor from ANSYS was integrated seamlessly into the framework for computational grid generation and material properties allocation, which enables easily modeling of structures with complex geometric features and material distribution. As mentioned above, a penalty function method was implemented in the LISA formulation to model the contact acoustic nonlinearity during wave damage interactions. A Coulomb model was used to capture the stick-slip motion at the crack interface. A non-reflective and absorbing boundary condition was enabled to minimize the model size and avoid undesired boundary reflections when required.

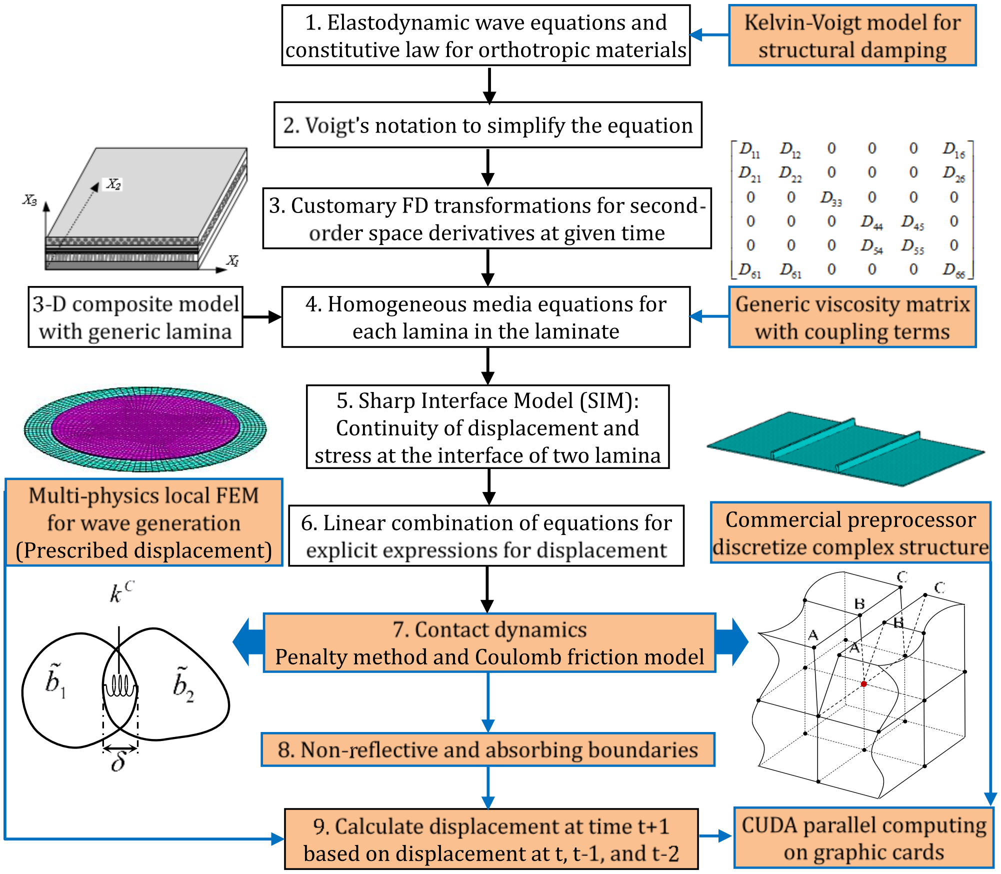

Figure 1: LISA framework for modeling guided wave generation, propagation, and nonlinear interaction with damage in complex structures.

2.2. GPU Implementation Using Compute Unified Device Architecture

There are two major characteristics of the current LISA formulation that enables the computation to be expedited on GPUs. First, LISA formulations are massively parallel. This is because the computation of a general node or a contact node only depends on the solutions of its eighteen neighboring nodes at the previous three time steps. Thus, the behavior of each node is independent from the others at the target time step, i.e., the computation of each node can be carried out individually in parallel. Second, the wave propagation simulation tasks usually require dense discretization of the structure, resulting in a computationally intensive problem. GPUs, with their massive concurrent threading feature, are suitable to handle such large size problems by distributing the workloads among a large number of functional units and carry out highly efficient parallel computing. In order to take advantage of the nice parallelizable feature of LISA and the superb computational capability of the powerful GPU device, the LISA procedure was implemented using CUDA. All the parameters are first established in the host memory (RAM). Then a copy of these parameters is sent to the device memory (GPU global memory) for it to be processed. The computation of each node is assigned to a functional thread, i.e., each thread will gather the displacements of its eighteen neighboring nodes at the previous three time steps, process the material properties in the eight surrounding cells, and execute the kernel to compute the displacement of this node at the current time step. Since one of the bottlenecks of a CUDA program is the data transfer between the device memory and host memory, only the required step results are gathered (every 20-30 steps depending on the frequency of the propagating waves) from the GPU to the CPU to minimize such data transfer.

3. Case Studies for Addressing Ultrasonic Wave Modeling Challenges

This section presents the case studies for addressing various ultrasonic wave modeling challenges, including guided wave propagation in anisotropic plates, Contact Acoustic Nonlinearity (CAN) simulation at crack interfaces, and wave propagation in geometrically complex structures. All these modeling efforts are compared with either experimental or numerical validation tests.

3.1. Guided Wave Propagation in Anisotropic Plates

Composite materials are drawing increasing attention in structural designs due to their strong and light-weight properties. However, their wide application has imposed considerable challenge to the SHM and NDE community, because they usually demonstrate anisotropic material properties and high damping characteristics. This brings much difficulty for ultrasonic based inspection techniques, since the elastic wave propagation and attenuation are direction dependent.

This subsection presents the numerical case study of damped guided wave propagation in anisotropic composite panels using LISA as well as the comparison with experimental measurements using Scanning Laser Doppler Vibrometry (SLDV). The multilayered composite specimens used in this study were a 12-layer unidirectional $[0]_{12T}$ CFRP composite plate and a 12-layer cross-ply $[0/90]_{3S}$ CFRP composite plate. They are manufactured from 0.125 mm thick pre-impregnated composite tape made from IM7 fibers and Cy-com 977-3 resin. Thus, the thickness of these composite panels is 1.5 mm. A 12.8-mm diameter and 0.23-mm thick circular piezo wafer was bonded on the center of the plate surface for wave generation.

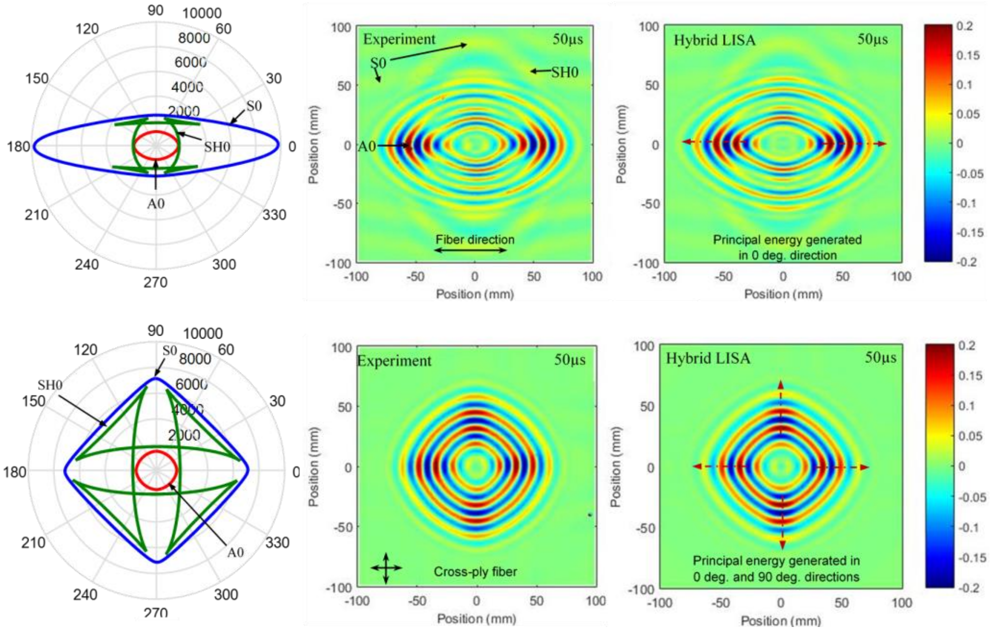

Figure 2: Comparison of guided wave propagation between LISA solution and SLDV measurement in a unidirectional composite panel (first row) and a cross-ply composite panel (second row).

Figure 2 shows the comparison between LISA solutions and SLDV measurements of guided wave propagation in composite panels. The first row corresponds to the results of guided wave propagation in the unidirectional $[0]_{12T}$ CFRP composite plate at 75 kHz. The second row corresponds to the results of guided wave propagation in the cross-ply $[0/90]_{3S}$ CFRP composite plate at 75 kHz. The first column presents the group velocity directivity curves of the fundamental wave modes S0, A0, and SH0 in these two composite plates. The second column shows the wavefield pattern from SLDV measurements, while the third column presents the LISA simulation results. It can be observed that the LISA simulation results agree well with experimental measurements, demonstrating LISA’s capability and accuracy in capturing wave propagation in arbitrary lamination scenarios.

To further demonstrate the importance of considering wave attenuation due to material damping, sensing signals at the coordinate location of (0 mm, 100 mm) in Figure 2 for the unidirectional composite panel case are presented in Figure 3, comparing three situations: experimental measurement, LISA result with damping, and LISA result without damping. The signal amplitudes are normalized to the maximum oscillation at the transducer. It can be seen that the conventional LISA without damping effects would overestimate the A0 mode amplitude. On the other hand, the viscoelastic LISA formulation can capture the anisotropic damping behavior for guided wave attenuation. It should also be noted that the damping effects have more influence on the A0 mode than the S0 mode. This is related to the motion characteristics of their mode shapes and wavelengths.

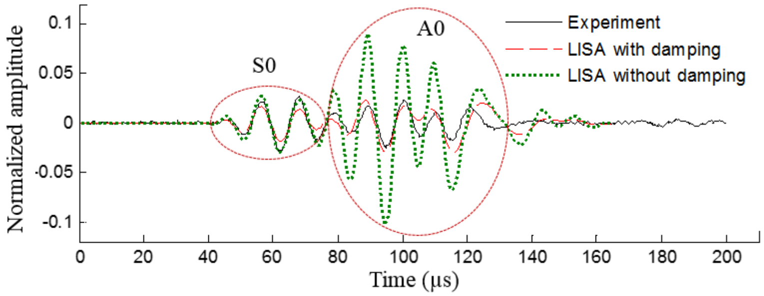

Figure 3: Simulation signal with and without damping effect and the measured signal at a point 100 mm away from the source normal to the fibers in a $[0]_{12T}$ composite laminate.

3.2. Contact Acoustic Nonlinearity at Crack Interfaces

Fatigue cracks may exist in a broad range of engineering materials and are considered precursors to catastrophic failures. Effective detection of fatigue cracks at their early stages is of critical importance and particular interest. However, unlike gross damage, the fatigue cracks are barely visible in their closed state, imposing considerable difficulty for the conventional ultrasonic techniques which are only sensitive to open cracks. On the other hand, nonlinear ultrasonic techniques have shown much higher sensitivity to incipient structural changes with distinctive nonlinear features, such as higher/sub harmonic generation, DC response, mixed frequency modulation response (sideband effects), and various frequency/amplitude dependent threshold behaviors.

This subsection presents the LISA modeling results of nonlinear interactions between guided waves and fatigue cracks. Figure 4 shows the benchmark model setup to compare LISA solution with commercial finite element results. It consists of a 500-mm long, 20-mm wide, and 5-mm thick aluminum strip. A 10-mm long through-thickness breathing crack is located in the center of the strip. A pair of in-phase line prescribed displacements (1 μm peak to peak value) were used to generate 100-kHz 10-cycle tone burst S0 guided waves into the structure. They will propagate along the structure, interact with the breathing crack, bring the crack information with them, and are finally picked up at the sensing point. The out-of-plane displacement at 10 mm right after the crack was recorded and post-processed for the convergence study.

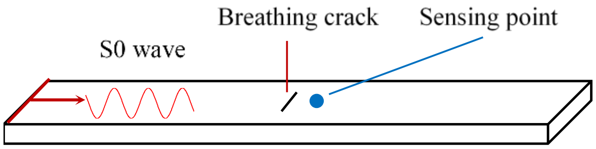

Figure 4: Benchmark problem to compare LISA solution with finite element results.

Figure 5 shows the verification of the contact LISA model against the ANSYS solution. It can be noticed that the signals agree with each other in time domain with merely slight differences. The frequency spectra shown in Figure 5b also demonstrated that the frequency components of fundamental excitation, low frequency DC component, second, third, even fourth higher harmonics compare very well with each other. Differences only appeared at very high frequency range, where the time step needs to be sufficiently small to generate accurate results or meaningful comparison between the two methods. This numerical verification against commercial finite element code attested the capability and validity of the new contact LISA model.

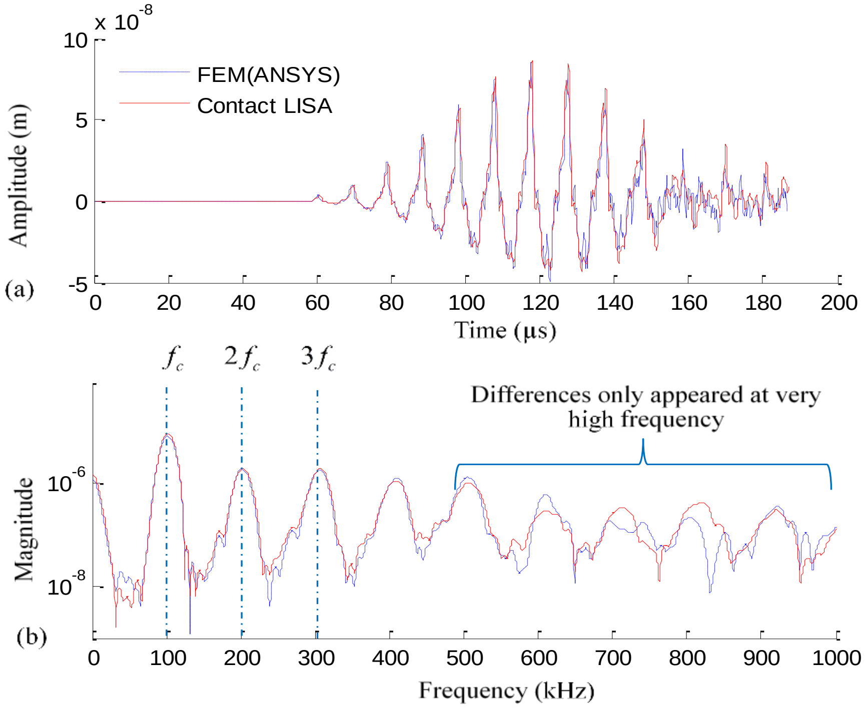

Figure 5: Contact LISA solution compares well with the result from commercial FEM package ANSYS: (a) time domain simulation signals; (b) frequency domain spectra.

It is worth of pointing out that the new contact LISA model also achieved much higher computational efficiency over the conventional nonlinear FEM simulation. Both computational tasks were conducted on an Asus ESC2000 G2 workstation with a 2.00 GHz Intel Xeon E2-2650 processor, 32 GB of 1.60 GHz memory, and an Nvidia GeForce GTX Titan graphics processor with 2688 CUDA cores. The FEM simulation with 279,900 degrees of freedom took around 19 seconds for each time step, resulting in a total computational time of 8 hours for 1500 time steps. On the other hand, LISA simulation with 648,120 degrees of freedom merely consumes around 0.043 second for each time step, resulting in a total computational time of 2.15 minutes for 3000 time steps. Thus, it is apparent that the new contact LISA model is much more efficient than the conventional nonlinear FEM simulation, while achieving comparable results.

The contact LISA algorithm also allows the consideration of the rough crack nature of practical fatigue cracks [Shen et al. (2018)]. Such effect is captured by implementing a random distribution of contact pairs along the crack interface, forming a 3D rough contact area with initial openings and closures. The roughness of the fatigue crack would impose considerable influence on the sensing signals. Figure 6 presents the wave damage interaction patterns under the frequency-sweeping excitation for both the idealized breathing crack case and the rough crack case. The out-of-plane displacement wave fields are plotted. For the breathing crack case, the superharmonic components with short wavelength can be clearly identified in the wave field. It can be observed that the amplitude and directivity appear to be much different at various frequencies. For the rough crack case, the random directivity scattering pattern and the mode converted, short-wavelength A0 mode can be clearly noticed. The low-frequency (DC) response is rather obvious in the out-of-plane displacement field. At different frequencies, the scattering pattern changed much as well.

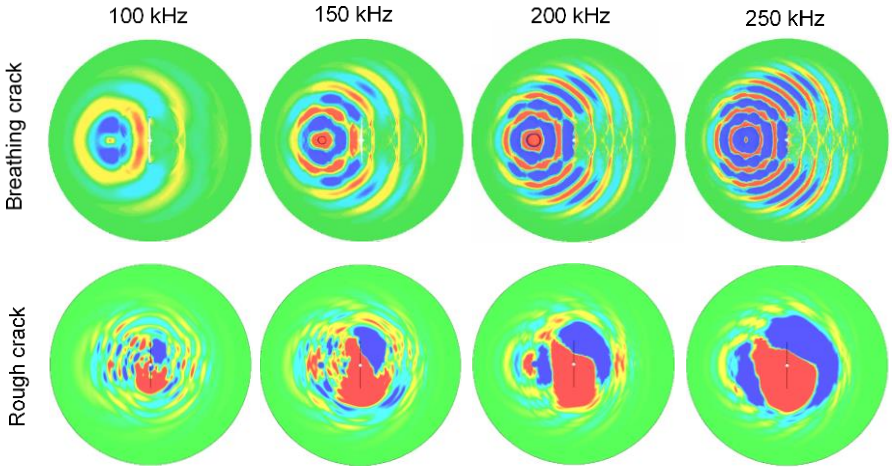

Figure 6: Wave damage interaction patterns under frequency-sweeping excitation.

3.3. Wave Propagation in Geometrically Complex Structures

The most commonly encountered modeling challenge comes from the large, complex structural geometries. It may not cause a concern in commercial FEM packages, but it remains a challenge for many of the newly developed computationally efficient schemes. LISA's seamless integration with commercial preprocessors enables the handling of geometrically complex waveguides. To substantiate this aspect, this section presents the numerical case study of utilizing LISA to model guided wave propagation in a rail track.

Figure 7 presents the LISA model for guided wave propagation and interaction with a notch in a BS 90A rail track. A 140 kHz 5-cycle tone burst is used for wave generation. The ultrasonic waves propagate along the rail track, interact with the notch, and are finally picked up at the sensing location. Absorbing Layers with Increasing Damping (ALID) is used on both ends of the model to eliminate boundary reflections. A 1-mm mesh size is adopted for the cross-sectional area, while a 2-mm mesh sized is deployed for the track direction. The time step according to the Courant–Friedrichs–Lewy (CFL) condition is 114.22 ns, which corresponds to a CFL number of 0.99. Figure 7 shows that the adopted mesh grid can capture the complex geometric details of the rail track. The LISA algorithm was implemented using CUDA technology and executed in parallel on GPUs (NVIDIA GeForce Titan X with 3072 CUDA cores). Although the entire model reached 8,968,401 DOFs, the GPU implementation and parallel computation allows remarkable modeling efficiency.

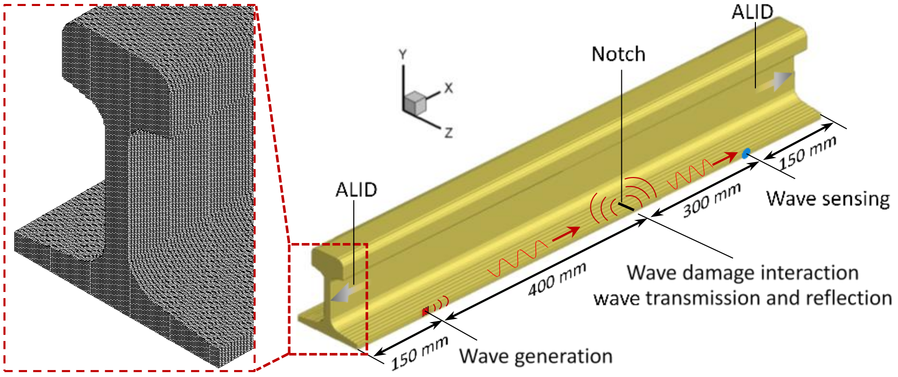

Figure 7: LISA model for guided wave propagation and interaction with a notch in a BS 90A rail track.

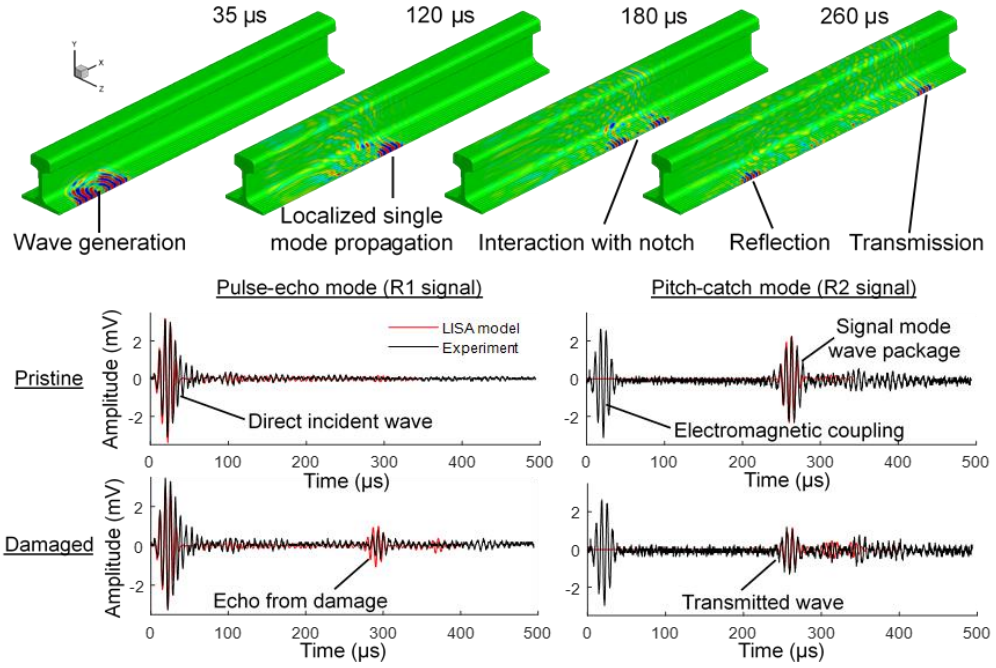

Figure 8: LISA simulation results and comparison with experimental measurements.

Figure 8 presents the LISA simulation results with snapshots showing wave generation, localized rail foot guided wave propagation, interaction with the notch, transmission, and reflection. It should be noted that dominant wave energy propagate in the rail track as the localized rail foot mode through careful tuning of transducer parameters and the excitation frequency. For the pristine case, no echo is found in the sensing signal, and large amplitude is found in the pitch-catch signal. When damage appears, obvious echo signal can be notice in the pulse-echo mode, and the transmitted energy captured by pitch-catch mode drops noticeably. Experimental data was collected through the research collaboration with the national rail transit electrification and automation engineering technology research center at the Hong Kong Polytechnic University. Note the active sensing signal from both experiments (black lines) and LISA simulation (red lines) agree well with each other, demonstrating LISA's high quality and prowess in modeling wave motion in complex waveguides.

4. Summary, Concluding Remarks, and Suggestions for Future Work

This paper presented the local interaction simulation approach for efficient modeling of linear and nonlinear ultrasonic guided waves for SHM and NDE applications. Three major modeling challenges were addressed: material anisotropy with damping effects, nonlinear interactions between guided waves and structural damage, as well as the geometric complexity of waveguides. Three case studies were presented: (1) wave propagation in anisotropic composite panels with experimental validations using the Scanning Laser Doppler Vibrometry; (2) nonlinear interactions between guided waves and fatigue cracks verified with the commercial finite element package; (3) guided wave propagation and damage detection in a rail track compared with experimental measurements. It was found that the LISA framework could accurately capture the direction dependent wave propagation and attenuation in composite plates. The nonlinear wave damage interactions can be captured by the contact LISA formulation with much higher computational efficiency than the commercial finite element package. For large, complex geometric waveguides, LISA framework demonstrated its great efficiency in carrying out heavy computation which is prohibitive for most conventional numerical approaches. This paper systematically demonstrated LISA's prowess for efficient modeling of transient dynamic guided wave phenomena in SHM and NDE damage detection procedures.

For future work, the modeling capability of LISA should be further extended and integrated to establish a powerful simulation platform for SHM and NDE system design.

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